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EFFECTS OF ENGINEERING DESIGN-BASED STEM APPROACH ON STUDENTS' CONCEPTUAL UNDERSTANDING, ENGINEERING DESIGN PERFORMANCE, AND SCIENTIFIC CREATIVITY

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Abstract. *The Filipino students demonstrated low scientific creativity as revealed by international assessments, prompting the urgent need for an effective educational approach to address this learning gap. In view of this, the present study examined the effect of integrating Engineering Design Process on STEM instruction (STEM-EDP) on students' conceptual understanding, engineering design performance, and scientific creativity. The study further identified the learning affordances and constraints encountered by the students during the implementation of STEM-EDP. Using educational action research with Plan-Do-Study-Act model, the study validated and implemented STEM-EDP lessons to a purposive sample of 108 students. Results show that the students' conceptual understanding, engineering design self-assessment, and scientific creativity significantly improved and demonstrated large effect sizes as indicated by Wilcoxon signed-rank test and effect size r. The thematic analysis highlighted the learning affordance (exploration of creative solutions, iterative problem-solving, reflection from learning experiences, and systematic procedure) and the constraints (time management in using EDP, learning references and resources, and background on the problem). Recommendations for the next action research cycles were also discussed.*

Keywords: *engineering design performance, conceptual understanding, engineering design process, scientific creativity, STEM education*

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Introduction

The rapid change in the world along with the 21st century education placed creativity as a critical skill, representing a distinctly human capability that remains resilient against digital revolution. This situation calls for creativity to be positioned as a core priority, especially in science education, where innovation and meaning in problem-solving is required. Creativity is an essential human capital in a society invulnerable to technological automation. Creativity also served as one of the foundations of social and economic progress across nations (Sorgo, 2012). It is used as an input to economic productivity and provides a support system for global competitiveness. Furthermore, creativity along with analytical thinking skills and flexibility are known as highly demanded skills in the year 2025, based on the Future of Jobs Report 2023 of the World Economic Forum (2020). This provided evidence that creativity, as a consistent top skill, is essential for a future society that is information-based and technology driven (World Economic Forum, 2020). This confronted the current educational system to reform the schooling to deliver quality education responsive to the new generation with high creativity to become globally competitive and meet the global standards (Daud et al., 2012).

In recent years, science education has undergone various educational reforms to respond to the evolving knowledge-based society and to the rising global demands for a workforce equipped with scientific literacy and skills. The current reforms directed science education to gradually place Science, Technology, Engineering, and Mathematics (STEM) education at the center of curricular development. STEM, as an academic field, has been recognized both locally and globally to be a powerful vehicle for economic and social development (Panergayo, 2023; Panergayo et al., 2022). This recognition can be attributed to the fact that STEM education equips students with skills that make them more employable and prepared to fulfill current and future labor demands, from a wide range of experiences to abilities (Partnership for 21st Century Skills, 2009).

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STEM education assumed a crucial role in the development of creativity among 21st century learners. It provides a conducive avenue to nurture creativity (Daud et al., 2012). Science subjects are creativity-fostering learning environments that support interaction among various factors, including domain-specific knowledge, divergent thinking, imagination, and visualization, and a social dimension (Hadzigeorgiou et al, 2012). Furthermore, the innate characteristics of science, allowing learners to receive various data and apply scientific processes in reference to its theoretical perspective, are aligned with the nature of the creative process (Mukhopadhyay & Sen, 2013). In this setting, nurturing creativity in science education became a focal figure to the creativity research in science learning domains. Conradty et al. (2020) elaborated that there are numerous science education curricula that go beyond conventional learning goals, which gradually emphasize creativity in science classrooms, placing creativity as a fundamental skill in the 21st century.

In the Philippines, the MATATAG Science Curriculum introduced engineering literacy alongside scientific, environmental, and technological literacies. The addition of engineering literacy to the overarching goals of Philippine science education facilitates the integration of the engineering design process (Department of Education, 2023). This integration aims to develop STEM skills and knowledge among students, offering opportunities to design and improve products and find solutions to community problems. In the 2022 Programme for International Students Assessment (PISA), however, the Philippines registered an average score of 14 points on the newly introduced creative thinking test, positioning the Philippines among the lowest performers out of 64 participating countries. This situation necessitates intervention to enhance creative thinking among Filipino students. Science curriculum reforms should integrate inquiry-based and problem-based learning to encourage students to explore, hypothesize, and innovate. In view of this, the study aimed to gather empirical evidence on the effectiveness of the engineering design process in fostering scientific creativity at the upper-secondary school level, specifically among STEM strand students.

Engineering Design Process

Engineering design has drawn attention due to its characteristics to improve students' aptitudes and dispositions for handling challenging, real-world problems (English & King, 2015; Purzer et al. 2015). Engineering Design Process (EDP) emerged as an effective instructional strategy to address the learning outcomes of the students in STEM-related fields, such as science, mathematics, and engineering. The EDP refers to a set of processes used by engineers to solve a problem. In fact, it has been defined by researchers and scholars in different ways in academic literature. For instance, the National Aeronautics and Space Administration (NASA) of the United States of America defined EDP as a series of steps engineers use to facilitate solving engineering problems. NASA states that engineers must ask a question, imagine a solution, plan a design, create a model, experiment and test the model, and improve the developed solution. The University of Colorado further contended that EDP underscores open-ended problem-solving, which prompts students to learn from failure, which in turn fosters students' abilities to create innovative and well-tested solutions to any challenge. In the study of Dym et al. (2005), EDP was described to refer to a systematic process involving concept application to develop a device or a system to address both the given objectives and existing constraints. In another study, Mangold and Robinson (2013), defined EDP as an iterative process of decision-making in which the fundamental knowledge in mathematics, science, and engineering is employed to develop an optimal solution to a problem. These existing descriptions in scholarly literature can be organized to strategically define EDP in the context of the study. The present study pertains to EDP as a systematic and iterative process to develop various solutions to problems grounded on the principles of science, mathematics, and engineering, and transforming them into creative products.

EDP emerged to be one of the widely available educational strategies for the implementation of STEM education (Hafiz & Ayop, 2019). The open-ended problem solving that is emphasized throughout the EDP helps students learn from their errors. This procedure develops students' capacity to come up with original responses to problems in any discipline. EDP as a pedagogical strategy allows students to follow an iterative procedure to apply their mathematical, scientific, and engineering knowledge to generate the most operative solution to a given problem (Hafiz & Ayop, 2019). It is claimed that EDP, as an approach to science teaching, is a variation of problem-based learning (Schnittka, 2009). Like problem-based learning, which provides learners opportunities to identify solutions to ill-structured, real-word problems, EDP integrates engineering practices to solve open-ended problems through developing innovative approaches or solutions using design thinking processes (National Research Council, 2012). The Next Generation Science Standards (NGSS) incorporated engineering design into the structure of science education by raising the level of engineering design to the same level of scientific inquiry when

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teaching all science disciplines across grade levels (National Research Council, 2012). This is to provide students with foundations in engineering design, which will make them equipped to face major societal and environmental problems in the future.

Scientific Creativity

Scientific creativity has a multitude of definitions available for consideration from different fields and perspectives. It can be defined from the viewpoints of creativity as a process, a personal trait, a press, or a product (Long et al., 2022). It is assumed to be the focal point of outcomes and those things that result from the creative process. Creativity manifests in the phenomenon in which a person communicates a novel concept, and this concept is the product. While there are various definitions of scientific creativity, there is a scholarly agreement that it refers to the development of original and functional ideas or solutions given a problem. Sternberg and Lubart (1996) and Sternberg (2022) defined creativity as the ability to produce outcomes that are both novel (i.e., original and unexpected) and appropriate (i.e., useful, adaptive concerning task constraints). Cropley (2011) defined creativity as depicting novel products that serve a useful social purpose, known as functional creativity. This is like the standard definition proposed by Runco and Jaeger (2012) and Amabile and Pillemer (2012). Bessemer and O'Quinn's model (1989), as cited by Norzaimalina et al. (2015), identified three important factors qualifying the creativity of the product, which are Novelty, Resolution, and Style.

Scientific creativity is a domain-specific creativity that drives human advancement by generating novel ideas and solutions across disciplines (Hu et al., 2010). Hu and Addey (2002) further defined scientific creativity as the application of scientific knowledge and skills to create original products of social and personal value. The further development characterized the Scientific Creativity Structure Model (SCCM), encompassing various dimensions improving technical products, advancing science, understanding phenomena, and solving scientific problems. Viewed from the perspective of a personal trait, scientific creativity is commensurate with fluency, flexibility, and originality. Fluency is the ability to generate numerous ideas given a content or problem domain. Flexibility involves the capacity to shift perspectives, approaches, or problem-solving strategies to explore diverse ideas and solutions. Meanwhile, originality pertains to the uniqueness, novelty, or innovative quality of ideas, theories, or solutions (Torrance, 2012). These three dimensions are integral to scientific creativity, enabling the generation of diverse ideas and innovative solutions to address complex scientific issues.

Effects of Engineering Design on Conceptual Understanding, Design Performance, and Scientific Creativity

Integrating EDP in science teaching has been reported to enhance students' cognitive aspects in terms of scientific knowledge (Fan & Yu, 2017), thinking (Yildiz et al., 2018; McFadden & Roehrig, 2018), and performance (Strimel et al., 2018) and non-cognitive features such as skills (English & King, 2015; Barak & Assal, 2018), attitude (Hathcock et al., 2015), motivation (Jackson et al., 2018), and self-efficacy (Leonard et al., 2016). This evidence placed EDP as a focal educational strategy in STEM education and as well as in science teaching and learning. Furthermore, Ngo (2024) revealed significant improvement in perception of science and physics learning through the EDP. This also enhances the learning outcomes of the students. Syukri et al. (2018) further revealed that a well-planned and systematic development of learning, based on EDP, had a high positive impact on students' achievement and skills, which in turn improves problem solving skills, thereby enhancing science learning. Utilizing engineering design can aid students in understanding how scientific knowledge applies to real-world problem-solving (Fortus, 2005). When students are involved in problem-solving within meaningful contexts, they are more inclined to engage critically and question experimental outcomes, rather than simply receiving the science content from the sources (Benenson, 2001). This suggests that engineering design activities offer chances to represent complex scientific concepts through tangible models, leading toward enhanced understanding of the lessons. Incorporating engineering design principles into science and mathematics instruction can further enhance the students' academic performance, as well as their interest in STEM careers (Standish et al., 2016). Moreover, Rusmana et al. (2021) uncovered that STEM-based learning, such as EDP, can effectively enhance engineering skills. It highlights that combining science with technology, engineering, and math positively engages students in the engineering design process and skill development.

EDP significantly enhances scientific creativity by integrating theoretical knowledge with practical application. It fosters innovative problem solving, drives technological advancement, and expands scientific understanding through real-world experimentation and implementation (Panergayo & Prudente, 2024). EDP is recognized as a

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variation of problem-based learning in science education (Schinittka, 2019). It offers a platform for exploring creativity in designing solutions that meet the required standards to address ill-defined challenges (Zeid et al., 2014). STEM-based learning activities enhance students' scientific creativity, as they explore various solutions every day. These activities create an enriched learning environment for idea explorations and imaginative thinking (Eroglu & Bektas, 2022). Gök and Sürmeli (2022) proved that engaging middle school students in scientific toy design activities, which follow the engineering design process, positively enhances scientific creativity. Similarly, Unver and Okulu (2022) contended that EDP in the classroom is effective in encouraging creative ideas. He further argued that by engaging in EDP as an iterative process, students are encouraged to think critically and creatively. Uzel and Bilici (2022) further revealed that engineering design-based activities tied to real-world problems enhance middle school students' skills by promoting hands-on problem solving, critical thinking, creativity, and collaboration, thereby solidifying their understanding and application of engineering concepts. While EDP is found to be an effective intervention for scientific creativity, there is a dearth of empirical evidence in the Philippine setting, particularly at the upper-secondary school level (Panergayo & Pelgone, 2023). Given the persistent challenges in students' creative performance, there is a pressing need to evaluate the effectiveness of the EDP in fostering scientific creativity within the contexts of Philippine STEM education.

Research Problem

The integration of EDP into STEM education has the potential to enhance conceptual understanding, engineering design performance, and scientific creativity. However, despite its recognized importance, the Philippines continues to face challenges in fostering creative thinking among students, as evidenced by their dismal performance in the 2022 PISA creative thinking test. This issue is compounded by the current limitation of the Philippine science curriculum, which lacks sufficient emphasis on engineering literacy and argumentation. Given the need to improve creative thinking and problem-solving skills of the students, it is crucial to investigate the effectiveness of STEM-EDP in enhancing scientific creativity, particularly in upper-secondary schools enrolled in the STEM strand. This study seeks to explore the effects of integrating STEM-EDP into the curriculum and identify the learning affordances and constraints encountered by the students in the process, to inform future curriculum reforms and instructional strategies aimed at promoting creativity and innovation in Philippine Science education.

Research Aim and Research Questions

Despite the proven effectiveness of the STEM-based Engineering Design Process (STEM-EDP) in promoting scientific creativity, there is limited empirical evidence supporting its application in the Philippine upper-secondary school context. The current curriculum largely emphasizes content knowledge, often neglecting creativity as a learning outcome in physics education. As an educational strategy, EDP engages students in solving ill-defined and open-ended problems through an iterative process, allowing them to learn from failure and develop innovative solutions. This makes EDP a promising approach to enhance scientific creativity among the students.

The study aimed to enhance the teaching of scientific creativity alongside conceptual understanding and engineering design performance by integrating STEM-EDP as an educational intervention. Grounded in the idea that creativity is integral to the EDP, STEM-EDP has emerged as a feasible method for fostering creativity in science context. Specifically, the following questions were addressed within this study:

1. What are the effect sizes of the STEM-EDP on the students' conceptual understanding, engineering design performance, and scientific creativity in an upper-secondary school physics class?
2. What are the learning affordances and constraints encountered during the implementation of STEM-EDP as perceived by the students?

Research Methodology

General Background

This study utilized an educational action research design with Deming's (1993) PDSA (Plan-Do-Study-Act) model (Donnelly & Kirk, 2015) using the iterative process described by Brydon-Miller et al. (2017). The study was conducted in an upper-secondary school department in one state university in Laguna, Philippines, involving 108 upper-secondary school students enrolled in the STEM strand. The 108 students were recruited as a purposive

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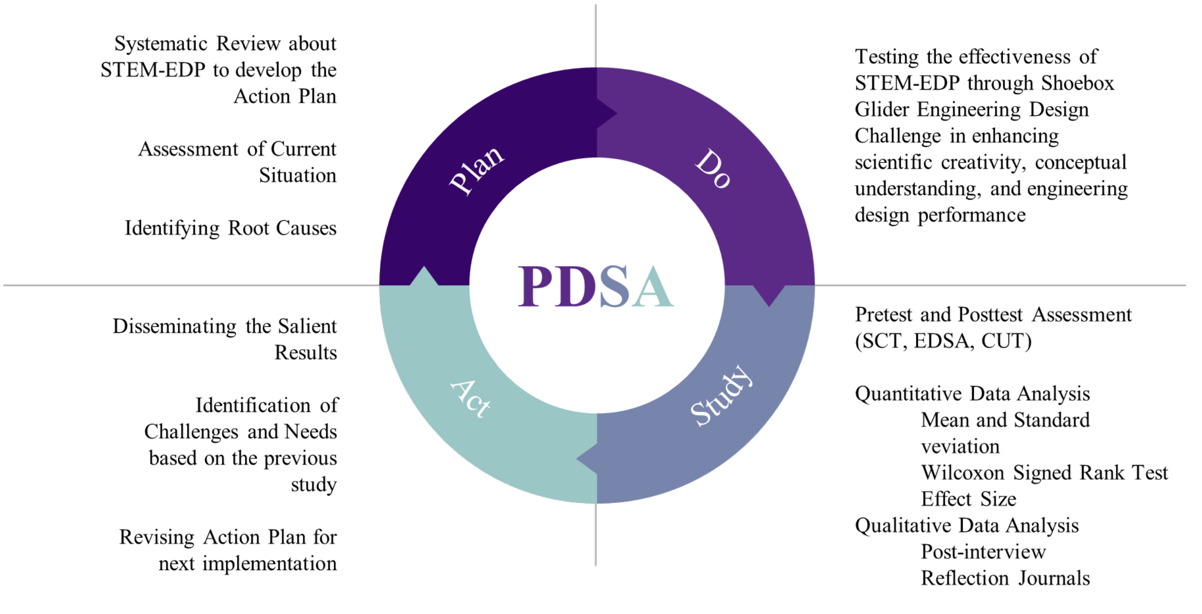
sample aligned with the objectives of the study, targeting to improve learning outcomes of students enrolled in the STEM strand. These are the students enrolled in the academic year when the study was implemented. Likewise, the objective was to enhance the teaching of scientific creativity in physics by introducing an intervention designed to be both challenging and engaging to STEM learners. The intervention was carefully aligned with the curriculum guide used in the course to ensure relevance and effectiveness. The hypothesis was that using STEM-EDP would motivate students to solve complex real-word problems, thereby applying both their creative and scientific knowledge in meaningful ways.

During the Plan phase, needs analysis involved initial assessment of conceptual understanding, engineering design performance, and scientific creativity. Additionally, a literature review was conducted to analyze the impact of design-based learning, such as EDP, on scientific creativity in STEM education. The findings from the needs analysis informed the establishment of the learning objectives and goals for integrating EDP into STEM instruction. In the Do stage, the expert-validated and pilot-tested STEM-EDP challenge from Space Structure of the National Aeronautics and Space Administration (NASA) was integrated into Physics lessons and was implemented in six weeks following the EDP Cycle (Massachusetts Science and Technology/ Engineering Curriculum Framework, 2006). The teaching and learning activities were directed towards a hands-on construction of a shoebox glider and subsequently enhancing its design to attain the greatest possible glide slope. The glide slope, defined as the ratio of the horizontal distance travelled to the change of height, served as the measurement to measure the performance of the glider. The development and testing including reiterations were conducted in 18 sessions, where each session lasted for one hour. The flow of the entire study is presented in Figure 1.

Figure 1
PDSA Model of the Study



Participants

The participants of the study were 108 Grade 12 upper-secondary school students, 52 female and 56 males, aged from 17 to 18 years old, enrolled in the Science, Technology, Engineering, and Mathematics (STEM) strand, coming from four intact classes. Most of the students came from middle- to low-income families, with limited access to advanced learning resources outside school. These classes were purposely selected from an upper-secondary school in the Laguna, Philippines, that served as the research site.

A purposive sampling technique was employed to target a specific group of students who could provide meaningful insights relevant to research questions. The recruitment process involved coordination with subject

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teachers and class advisers. Information about the study, including its purpose, procedure, and voluntary nature, was disseminated through classroom announcements and digital communication. Interested students were invited to attend an orientation session, where the study was explained in detail, and an informed consent form was distributed.

Instrument and Procedures

In the plan phase, the goal was to enhance students' conceptual understanding, engineering design performance, and scientific creativity through the integration of STEM-EDP. A literature review was conducted to guide the intervention design, aligned with the physics curriculum and is feasible for a design-based learning environment. Three main instruments were prepared: Conceptual Understanding Test - researcher-made, content-validated 20-item parallel tests administered before and after the intervention; the Engineering Design Process Self-Assessment- a 15-item self-rating scale based on a 3-point Likert format to measure students perceived engagement in the EDP; and the Scientific Creativity Test – a modified and validated six-item instrument originally developed by Hu and Addey (2002), designed to assess creative thinking in scientific context.

During the Do phase, the STEM-EDP intervention was implemented with 108 Grade 12 upper-secondary school students. The learning experience was delivered using EDP-based learning activities. To control potential confounding variables, students' prior knowledge was measured through a pretest to establish baseline data. The same teacher-researcher implemented all instructional sessions carefully following the validated lesson plans. All participants received equal instructional time, learning materials, and assessment tools to minimize variability in teaching delivery and learning conditions. This facilitates strengthening the internal validity of the study despite the absence of a control group. Students participated in an engineering design challenge, which required them to collaboratively design, build, test, and iterate on shoebox gliders. The primary objective was to craft an initial iteration of the shoebox glider and subsequently enhance its design to achieve the greatest possible glide slope. The glide slope, defined as the ratio of the horizontal distance travelled to the change of height, serving as the measurement to measure the performance of the glider.

They were grouped into teams of four, with each member assuming a specific engineering role. The Design Engineer, who sketched and outlined the glider design, ensuring that it met the identified criteria; the Technical Engineer, who was responsible for the assembly, maintenance, and modifications of the glider's structural components; the Operation Engineer, who set up and executed the flight tests, ensuring consistent testing conditions; and the Technical Writer, who documented the design process, recorded test results, and compiled data through written reports, photos, and videos. While each role was assigned to one individual, all team members collaborated across tasks, sharing knowledge and assisting with various aspects of the design, testing, and documentation.

The team completed at least two iterations of the glider design, with each iteration undergoing a minimum of three test flights to measure performance, specifically focusing on the glide slope and flight duration. The Operation Engineer collected performance data during each test, such as glide slope and flight duration, while the Technical Writer documented the entire process. The Design and Technical Engineers analyzed the data to identify the area for improvement, refining the design for the next iterations. This iterative process ensured continuous evaluation and optimization, with the goal of improving the glider's aerodynamic performance through collaborative problem-solving using the EDP framework.

Data Analysis

The Study and Act phases involved the collection of data throughout the implementation. Pre- and post-assessments using a researcher-developed Conceptual Understanding Test, and adapted Engineering Design Self-Assessment Survey (NASA, 2015), and Scientific Creativity Test (Hu & Addey, 2002) were conducted. The instruments used established high content validity and internal consistency, as revealed by computed Cronbach's alphas for each instrument emerging to be greater than the threshold, 0.70. The students are given a two-hour period to accomplish all the tests. This allowed me to gain empirical evidence on whether engineering design challenges can improve or not improve my target learning outcomes among the students. The results from the assessments were subsequently analyzed using the Wilcoxon signed-rank test and the effect size r. Semi-structured interviews and reflective essays were also used with expert-validated guide questions to uncover the learning affordances and constraints encountered during the STEM-EDP teaching. The interviews involved 10 selected students sharing insights on learning challenges and benefits. They were selected based on their responses to the reflective essays.

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The reflective essays allowed all participants to express their personal reflections on the affordances and constraints of the process. These qualitative data were further analyzed using Braune and Clarke's (2017) six-phase guide for thematic analysis. This involved identifying, coding, and interpreting themes related to students' experiences, challenges, and perceptions during STEM-EDP.

Research Results

The following tables show the descriptive and inferential statistics to verify the hypothesis suggesting STEM-EDP can improve the students' performance.

Table 1
Descriptive Results of Conceptual Understanding, EDP Self-Assessment, and Scientific Creativity

Variables		$\bar{X}$	*SD*
Conceptual Understanding	Pre	12.17	3.88
	Post	18.57	4.92
Engineering Design Performance	Pre	11.48	5.50
	Post	22.34	4.15
Scientific Creativity	Pre	79.29	30.53
	Post	112.56	41.65

Table 2 shows the mean performance of the students before engaging in the engineering design challenge. It reveals the assessment results in conceptual understanding ($\bar{x}$ = 12.17, *SD* = 3.88) engineering design self-assessment ($\bar{x}$ = 11.48; *SD* = 5.50), and scientific creativity ($\bar{x}$ = 79.29, *SD* = 30.53). It can also be observed that the variability of the data in conceptual understanding and engineering design self-assessment is low, indicating low variability. On the other hand, the standard deviation for scientific creativity test scores is 30.53, which indicates high variability. This outcome can be attributed to the nature of scientific creativity and the test used to assess it.

Shapiro-Wilk Test was used to determine the normality of the data. The data shows that the significant values of conceptual understanding (p = .037, 0.012), engineering design performance (p = 0.011, <0.001), and scientific creativity (p = .003, 0.010) before and after intervention, respectively, are all less than 0.05, indicating that the data obtained are not normally distributed. In this effect, the Wilcoxon Signed Rank Test was used to determine whether the performance of the students improved after engaging in engineering design challenges.

Table 2
Wilcoxon Signed Rank Test Results for Students' Conceptual Understanding, Engineering Design Self-Assessment, and Scientific Creativity

Variables	*z*	*p*	*r*
Conceptual Understanding	-8.627	< .001	.59
Engineering Design Performance	-8.860	< .001	.60
Scientific Creativity	-8.338	< .001	.57

Table 3 shows that the students' conceptual understanding (z = -8.627, p < .05, r = .59), engineering design self-assessment (z = -8.860, p < 0.05, r = .60), and scientific creativity (z = -8.338, p < .05, r = .57) significantly improved as indicated by Wilcoxon signed-rank test. This implies that implementing STEM-EDP and allowing the students to perform the EDP cycle can elicit substantial changes in their learning outcomes. Furthermore, all the computed effect sizes can be interpreted as large effect sizes, signifying that the observed effect is substantial and meaningful.

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Figure 2
Mean Pretest and Posttest Scores in Scientific Creativity Test

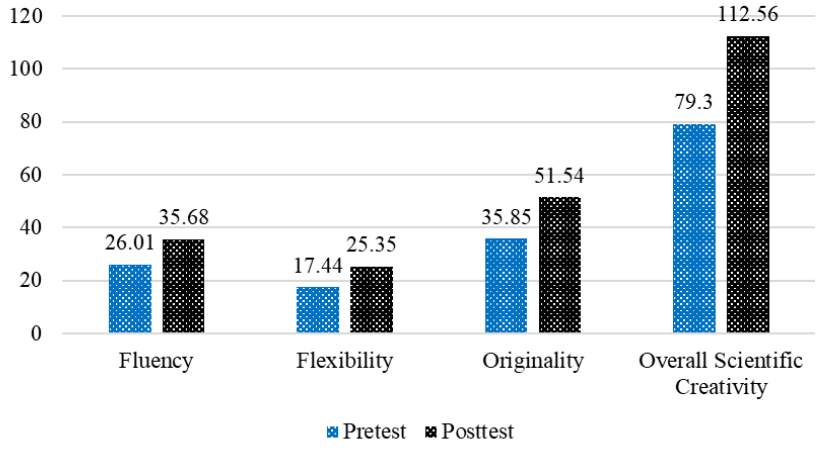

Figure 2 shows the mean pretest and posttest scores of the students in scientific creativity tests in terms of fluency, flexibility, and originality. It reveals that the posttest scores are considerably higher compared to the pretest scores, indicating an improvement in the performance of the students.

Table 3
Wilcoxon Signed Rank Test Results for Students' Scientific Creativity

Variables	*z*	*p*	*r*
Fluency	-7.764	< .001	.52
Flexibility	-8.803	< .001	.60
Originality	-7.495	< .001	.51

Wilcoxon Signed Rank Test for Students' Scientific Creativity displays that the students' fluency (z = -7.764, p < .05), flexibility (z = -8.803, p < .05), and originality (z = -7.495, p < .05) significantly improved based on the computed z- and p-values as presented in Table 3. It suggests that all dimensions of scientific creativity were largely affected by STEM-EDP in the present study.

The thematic analysis highlighted seven key themes that encapsulate the learning affordances and constraints with the STEM-EDP. The affordances include exploration of creative solutions, iterative problem-solving, reflection from learning experiences, and systematic procedure, while the constraints are related to time management in using EDP, learning references and resources, and background on the problem.

Exploration of creative solutions

The first theme underscores the role of EDP in fostering creativity, idea generation, and effective material selections for the development of a prototype glider. The iterative nature of the EDP is evident in the students' research efforts, where they actively explore feasibility of ideas and use the process to brainstorm and generate innovative concepts for the glider. Moreover, the students effectively employ the ideation within the EDP framework, considering various materials and solutions to address the given problem. The integration of EDP not only aids in focusing on crucial aspects but also facilitates continuous improvement to generate creative and innovative solutions to address the problem. The role of EDP extends beyond being a technical procedure by providing additional information that guides the students in creating the effective product. These instances underscore how EDP encourages students to explore creative solutions, fostering innovations, problem-solving skills, and a clear understanding of the design process.

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Iterative problem-solving

The second theme, iterative problem-solving, is exemplified throughout the EDP as shown by the engagement of the students in the whole process. The students perceived EDP as a dynamic and effective approach to overcome the challenges in the development of the prototype glider. The commitment of the students to iterations and adjustments based on the EDP allows them to continuously improve the features of the glider, ensuring the effectiveness of the glider to address the identified constraints. The iterative nature of the EDP is further emphasized as the students apply ideas and redesign prototypes multiple times, learning from errors and gradually attaining better results. Evidently, EDP serves as a guide in the trial-and-error processes, testing the glider's reach and fostering an improvement mindset. The student's persistence in trying and keeping on improving the glider until the optimal solutions are found reflects the iterative essence of problem-solving within the EDP framework. In summary, the iterative problem-solving highlights the integral role of the EDP in fostering adaptability, resilience, and continuous refinement throughout the design and development process.

Reflection from learning experiences

The third theme, reflection from learning experiences, emerges as a fundamental aspect of the students' engagement with the EDP. Through the various circumstances, the students express the significance of reflection in enhancing their understanding and refining their approach to glider development. It can be noted that they acknowledge the commonality of repeating and reflecting within the EDP, stressing the iterative nature of the problem-solving journey. The EDP is also known for providing a structured platform for planning and reflecting on their design plans, contributing to their deeper understanding of the challenges encountered within the EDP. Reflection is also evident in the students' recognition of weaknesses in their glider and the identification of potential challenges, exemplifying their proactive stance. Furthermore, EDP aids in determining possible solutions while acknowledging the constraints, fostering a reflective learning process. Reflection from learning experiences shows how the EDP cultivates a culture of reflection, enabling the students to learn from their mistakes, adapt strategies, and improve their problem-solving skills.

Systematic procedure

The fourth theme, systemic procedure, is very evident in the students' experiences with the EDP. The students accept the fact that EDP provided a structured and organized framework for the development of the shoebox glider. The EDP serves as a comprehensive roadmap, guiding the students through each step of the design process. This systematic approach is shown as the students focus on crucial aspects and plan various features essential for developing an effective glider. Students note that EDP does not only guide them but also allow them to think critically in developing prototypes, incorporating the step-by-step procedure that enhances the performance of the glider. Similarly, EDP as a framework ensures a methodical approach in creating, implementing, and assessing plans from the conceptualization of the design to the actual physical design. It also contributes to the goal setting of the team to clearly identify the objectives and possible problems that may be encountered. Hence, the EDP instills a sense of direction, organization, and methodical progression in the students' pursuit of creating effective solutions.

Time management in using EDP

The fifth theme, time management in using EDP, was consistently highlighted by the students stating the challenge in managing time effectively throughout the EDP. Their accounts suggest that they experienced a struggle to balance limited time and materials, compounded with the conflicts arising from the scheduling of the activities. This emphasizes the critical role of time management in the successful implementation of EDP in developing the shoebox glider. The experience of the students stresses the importance of handling their time wisely, as they engage in the challenges with their other commitments and make the best use of their limited resources to ensure project accomplishment. To address this challenge, integrating scaffolded timelines and checkpoints and allocating dedicated in-class work sessions may help learners manage tasks more efficiently while accommodating other academic responsibilities.

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Learning references and resources

The sixth theme, learning references and resources, is often emphasized in the students' experiences as they frequently mention the lack of readily available learning materials and resources. They express difficulty in gaining knowledge and understanding the mechanical aspects of the glider project. The absence of learning resources and reliable references is evident, highlighting the need to bridge the knowledge gap. This underscores the necessity to provide active support to the students in designing a learning environment with available resources to support their journey using EDP. In simpler terms, the students often struggle in accomplishing the engineering design project due to limited references, specifically the mechanical aspects of the target product to be developed. To bridge the gap, curated digital resources, simplified engineering concept ideas, and teacher-facilitated reference banks can be provided. This ensures equitable access to foundational knowledge and supports informed design choices during the EDP process.

Background on the problem.

In the seventh theme, the students repeatedly highlight the challenge of a lack of background in dealing with the shoebox glider project. They state that planning and designing the glider has become complicated because they have no idea which design must be considered and would be effective. The overarching issue is the perceived deficiency in knowledge and interest in mechanical transport systems. This lack of understanding extends to the construction phase, where the notable challenge is the actual building of the glider. Students emphasized personal adjustments and the absence of prior experience in constructing a glider, underscoring the need for fundamental knowledge and practical skills to address the challenges effectively.

Discussion

The findings showed that the STEM-EDP can significantly improve students' conceptual understanding. This can be attributed to the several learning scenarios where students were tasked to design and optimize shoebox gliders. They were given learning avenues to apply Newton's laws of motion, principles of aerodynamics, and energy transfer to make their prototypes glide farther. During these hands-on activities, students actively questioned why their glider stalled or dropped too quickly and returned to relevant physics concepts to address the problems. This result aligns with Fan and Yu (2015), Fan et al. (2017), and Schinittka et al. (2019), who argued that a STEM-oriented engineering approach can substantially improve conceptual knowledge of high school technology education. Parallel observations were established by Barret et al. (2014) showing that an interdisciplinary module from meteorology with engineering is successful in promoting science learning, particularly at the recall and understanding levels.

The present study also uncovered that the engineering design performance was significantly enhanced by STEM-EDP. During the shoebox glider project, students initially struggled with selecting the appropriate materials and achieving the stable flights. However, the iterative designing and documentation of flight data inform modifications of the shoebox glider. Evidence-based improvement of the design is a key feature of engineering. Likewise, the assignment of engineering roles also helps with accountability and collaboration, allowing each student to gain deeper experience of the engineering design cycle. English (2018) and Strimel et al. (2018) similarly argued that EDP learning enhances students' design performance by improving their satisfaction with redesign, material knowledge, measurement, and spatial skills. This indicates further support for the incorporation of engineering design into STEM education towards developing students' design abilities and understanding.

The same observation was established with scientific creativity being fostered by STEM-EDP implementation. The creativity development was conveyed by integrating theoretical knowledge with practical application and engineering practice. It offers a platform for exploring creativity in designing solutions that meet the required standards to address ill-defined challenges (Zeid et al., 2014). Likewise, STEM-based learning activities enhance students' scientific creativity, as they explore various solutions in their daily lives. These activities create an enriched learning environment for idea explorations and imaginative thinking (Eroglu & Bektas, 2022). Gök and Sürmeli (2022) proved that engaging middle school students in scientific toy design activities, which follow the EDP framework, positively enhances scientific creativity. Similarly, Unver and Okulu (2022) contended that EDP in the classroom is effective in encouraging creative ideas. He further argued that by engaging in EDP as an iterative process, students are encouraged to think critically and creatively and improve their understanding of the lessons. Uzel and Bilici (2022) further revealed that engineering design-based activities tied to real-world problems enhance middle school students' skills

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by promoting hands-on problem solving, critical thinking, creativity, and collaboration, thereby solidifying their understanding and application of engineering concepts.

The thematic analysis highlighted seven key themes that encapsulate the learning affordances and constraints with the STEM-EDP. The affordances include exploration of creative solutions, iterative problem-solving, reflection from learning experiences, and systematic procedure. These features foster deeper engagement and meaningful learning. It is further revealed that a well-planned and systematic development of learning is a characteristic of an effective EDP instruction (Syukri et al., 2018). On the other hand, the constraints related to time management in using EDP, learning references and resources, and background on the problem, posed challenges in fully maximizing the design process. Since the EDP follows a multi-step process, it requires more instructional time (Long et al., 2020). It is also verified that students' prior knowledge is essential in solving engineering design challenges (Panergayo & Prudente, 2024). Thus, it is imperative that the design challenge is relevant to the students' experience.

Conclusions and Implications

The findings underscore a statistically significant enhancement in students' conceptual understanding, engineering design performance, and scientific creativity through the implementation of STEM-EDP. This improvement highlights the transformative impact of integrating theoretical knowledge into practical applications via EDP framework in STEM teaching and learning. Specifically, students demonstrated increased fluency, flexibility, and originality in idea generation, along with improved ability to apply scientific knowledge and engineering principles in solving real-world problems. STEM-EDP provides a venue for the students to systematically explore multitudes of ideas, design creative solutions, and demonstrate real-life problem-solving with critical thinking and creativity. STEM-EDP further gives students opportunities to learn from their mistakes and subsequently address it for an improved outcome. These findings affirm the value of EDP as an instructional model aligned with 21st-century skills and global education priorities. In the light of these findings, this study recommends the continued integration of EDP in STEM education to foster other STEM skills and knowledge among the students. Globally, this work contributes to the growing discourse on design-based STEM instruction and offers empirical evidence from the global south, particularly in the Philippines, on how EDP may be leveraged to elevate educational outcomes in resource-limited contexts. The identified learning constraints, such as time management, access to learning resources, and relevance of the problem, should be addressed for future implementation to optimize the learning experience. For the next cycles of this action research, with the advent of Artificial Intelligence (AI), future researchers can explore the role of Generative AI (GenAI) in implementing EDP in STEM education to further improve the implementation by addressing the identified constraints in the present study. Following the successful implementation of the present study, future research may intend to develop, validate, and implement modules integrating AI into EDP in STEM education (henceforth, AI-STEM-EDP) to further improve STEM learning outcomes and potentially address the learning problems encountered in the present study. The next cycles may highlight the transformative effect of GenAI in optimizing EDP experience in STEM learning, identifying the role of GenAI to support engagement of students in the EDP framework.

Declaration of Interest

The authors declare no competing interest.

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